Appendix A-2
Rocket Pioneers

Konstantin Eduardovich Tsiolkovskiy (1857–1935) was sixteen years old when he was struck by a fascinating idea: Why not use centrifugal force to launch a spacecraft from earth? He became so excited about his idea that he could not sleep and wandered about the streets of Moscow all night, thinking about it. By morning, however, he saw the flaw in the concept. The experience had a profound effect on his later activities. Throughout his life, he continued to dream of flying to the stars; when he did so, he felt the same excitement as he had on that memorable night.[1] Tsiolkovskiy became the first to develop the theory of rocket flight and the first to consider hydrogen-oxygen to propel rockets.

Born of poor parents, Tsiolkovskiy lost his hearing at the age of nine and with it went the normal social relationships and education of children in his village, 900 kilometers east of Moscow. He became an avid reader and daydreamer, educating himself and qualifying as a schoolteacher in spite of his deafness, little guidance, and lack of books. Tsiolkovskiy's father, a forester, encouraged his son to build models, do physical labor, and be self-reliant. His mother showed him a collodian balloon filled with hydrogen when he was eight.* At fourteen, Tsiolkovskiy attempted to make a paper balloon filled with hydrogen but failed. He later developed the idea of a metal dirigible and published papers on the notion. He became interested in winged flight also and built a model which his father proudly showed to guests. In his twenties, he became involved with steam engines, fans, and pumps but after building a few he realized that his talents lay more in the direction of analyses and theoretical studies.[2] All of Tsiolkovskiy's rocket contributions are theoretical; he did not attempt experiments.

Tsiolkovskiy was a prolific writer on rockets and other subjects, displaying a remarkable insight into physical phenomena. He did not possess advanced academic credentials, yet he was recognized and accepted by eminent scientists for his contributions. In 1891 he sent a paper on the theory of gases to the Petersburg Physico-Chemical Society where it was well received by the members, including Dmitri Mendeleyev, famed Russian chemist. After a later contribution on the mechanics of

*Flexible collodian, made by dissolving guncotton in alcohol and ether and adding balsam and castor oil, was commonly used for making small balloons in the latter half of the nineteenth century. Tsiolkovskiy's mother may have bought a hydrogen-filled collodian balloon from an itinerant peddler.

animal organisms, Tsiolkovskiy was unanimously elected a member of the Society.

Of Tsiolkovskiy's many contributions to rocket technology, the best known is the theory of rocket flight which he developed from the laws of motion.[3] In its simplest form, the velocity of a rocket can be expressed as:

$$V = V_j \ln(M_o / M_e)$$

where V is the maximum velocity of the rocket in gravity-free, drag-free flight, V_j is the rocket exhaust jet velocity, ln is the natural logarithm, M_o is the initial or full rocket mass, and M_e is the empty rocket mass. This equation is called the Tsiolkovskiy equation in fitting tribute to the great pioneer.

The Tsiolkovskiy equation states a key relationship for understanding the advantages and disadvantages of liquid hydrogen as a fuel. The equation shows that rocket vehicle velocity is directly proportional to the rocket exhaust jet velocity. The latter is essentially constant for a given rocket design, propellants, and operating conditions. It depends upon the amount of heat energy released during combustion, the combustion pressure, the combustion products, and the nozzle for expanding the gases.

The second term of the Tsiolkovskiy equation, $\ln(M_o/M_e)$, involves two masses differing only in the amount of propellant (fuel and oxidizer) expended. The initial or full mass includes everything—payload, vehicle structure, tanks, engines, controls, guidance, and propellants. The empty mass is the initial mass minus the propellants that have been expended. During operation, the continuous burning of propellant and expelling of exhaust means that the total mass of the vehicle is continuously decreasing, starting with M_o and ending with M_e. Tsiolkovskiy understood this well, deriving the equation of flight based on the conservation of momentum, integrating, and using the initial and final conditions of the rocket to obtain his equation.*

Tsiolkovskiy explained the mass ratio term by showing that if the mass ratio is written as a geometric progression, the corresponding relative velocity ratios are an arithmetic progression.[4] As an example, he chose a progression of mass ratios to the base 2 and computed velocity ratios relative to the velocity ratio for a mass ratio of 2. This gave the geometric and arithmetic progressions shown in the first two rows of figure 59. The other relationships in the figure show the actual values of mass ratios and velocity ratios and also the former in terms of propellant mass fraction and the useful range for rockets.†

Examination of the values of figure 59 shows why there is an incentive for rocket designers to make the vehicle's structure, engines, guidance, and controls as light as possible, for they and the payload constitute the empty mass. Every kilogram shaved

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* Applying the conservation of momentum to rocket flight without drag or gravity loss gives $dm\, V_j = m\, dv$, where m is vehicle mass, d the derivative, V_j exhaust jet velocity (assumed constant), and v is flight velocity at the time the mass is m. Separating the variables and integrating gives $v/V_j = -\ln m + C$, where C is the constant of integration. Using initial conditions ($v=0$, $m=M_o$) to solve for C gives $C = \ln M_o$; the equation becomes $v/V_j = \ln(M_o/m)$, the vehicle velocity v when its mass is m. The rocket reaches its maximum velocity, V, when all propellant is expelled; at this time, $m = M_e$ and $v = V$. Substituting these gives Tsiolkovskiy's equation.

†Since the mass of propellant expended (M_p) is the difference between initial mass (M_o) and final mass (M_e), mass ratios can be expressed in terms of any two. Tsiolkovskiy later used the ratio M_p/M_e, now known as the Tsiolkovskiy ratio. In the United States, the propellant mass fraction M_p/M_o is often used; it is easy to visualize physically.

TSIOLKOVSKIY EQUATION, $V = V_j \ln \frac{M_o}{M_e}$, WHERE V = ROCKET VELOCITY, V_j = EXHAUST VELOCITY,

ln = NATURAL LOGARITHM, M_o = FULL MASS, AND M_e = EMPTY MASS

MASS RATIO, M_o/M_e (AS GEOMETRIC PROGRESSION)	2^1	2^2	2^3	2^4	2^5	2^6	2^7
VELOCITY RATIO, V/V_j (RELATIVE TO V/V_j FOR $M_o/M_e = 2$)	1	2	3	4	5	6	7
MASS RATIO, M_o/M_e (SAME AS FIRST ROW)	2	4	8	16	32	64	128
ACTUAL VELOCITY RATIO, V/V_j	.693	1.39	2.08	2.77	3.47	4.16	4.85
FRACTION OF TOTAL MASS THAT IS PROPELLANT (FUEL + OXIDIZER)	.500	.750	.875	.938	.967	.984	.992

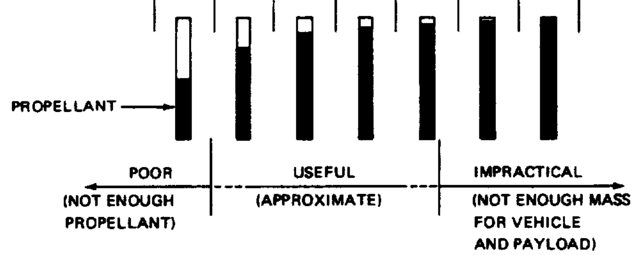

Fig. 59. Tsiolkovskiy's equation of rocket flight, neglecting drag and gravity. He illustrated the relationship by the geometric progression of the first row and the arithmetic progression of the second. The other rows illustrate the same relationship in other forms.

off the vehicle hardware means either a kilogram of payload gained or an increase in mass ratio and hence, vehicle velocity. By this reasoning, it can also be seen that given a choice, vehicle designers prefer dense propellants, for a greater propellant load can be put in a given tank size and mass. This is one of the reasons many investigators avoided liquid hydrogen, which has the lowest density of any fuel.

The progressions of figure 59 also show that in the higher mass ratios, gains in velocity come slowly. This diminishing return effect focuses attention on the other term of Tsiolkovskiy's equation, exhaust jet velocity. How can it be increased? By using fuels yielding higher heat energy, which translates into higher exhaust jet velocity. Tsiolkovskiy recognized the rocket as a heat engine and was aware of Joule's measurement of the mechanical equivalent of heat. It follows that the more heat that could be generated per kilogram of burning propellants, the greater the amount of work that could be done. He therefore searched the chemistry texts, particularly Mendeleyev's *Principles of Chemistry*, to find the fuels giving the highest heat per unit mass of reactants.[5] From what was known about heats of combustion by the start of the twentieth century, it is not at all surprising that Tsiolkovskiy became the first to propose the use of liquid hydrogen and oxygen to propel a rocket, which he did in his classic "Exploration of the Universe with Reaction Machines," first published in 1903.[6] Tsiolkovskiy used a heat of formation of water of $16 \cdot 10^6$ joules per kilogram (from reacting hydrogen and oxygen) and recognized that some heat would be expended in

converting liquid hydrogen and liquid oxygen to their gaseous states.* He converted this heat of formation into mechanical energy and obtained a potential energy of 1633 kilogram-meters. Using Newton's relationship between potential and kinetic energy, Tsiolkovskiy calculated the exhaust jet velocity of a liquid hydrogen–liquid oxygen rocket as 5700 meters per second.† Using this value, he calculated vehicle velocities for a range of mass ratios. For example, at a mass ratio M_o/M_e of 5, vehicle velocity was 9170 meters per second. Tsiolkovskiy preferred a mass ratio of 5, which means that 80 percent of the vehicle mass is propellant, because he calculated this ratio gave the greatest utilization of propellants.‡

In his 1903 paper, Tsiolkovskiy described a manned rocket (fig. 60):

> Visualize . . . an elongated metal chamber . . . designed to protect not only the various physical instruments but also a human pilot . . . . The chamber is partly occupied by a large store of substances which, on being mixed, immediately form an explosive mass. This mixture, on exploding in a controlled and fairly uniform manner at a chosen point, flows in the form of hot gases through tubes with flared ends, shaped like a cornucopia or a trumpet. These tubes are arranged lengthwise along the walls of the chamber. At the narrow end of the tube the explosives are mixed: this is where the dense, burning gases are obtained. After undergoing intensive rarefaction and cooling, the gases explode outward into space at a tremendous relative velocity at the other, flared end of the tube. Clearly, under definite conditions, such a projectile will ascend like a rocket . . . . The two liquid gases are separated by a partition. The place where the gases are mixed and exploded is shown, as is the flared outlet for the intensely rarefied and cooled vapors. The tube is surrounded by a jacket with a rapidly circulating liquid metal [mercury]. The control surfaces serving to steer the rocket are also visible.[7]

The fuel in this rocket is labeled "hydrocarbon," although in the article Tsiolkovskiy discussed hydrogen-oxygen more than any other fuel. In an article in 1911, summarizing work to that time, the caption to a drawing of his 1903 rocket showed liquid hydrogen as the fuel.[8]

The hydrogen-oxygen combination greatly appealed to Tsiolkovskiy because the thermal energy released in its reaction was the highest he knew. In his initial enthusiasm, he brushed aside the difficulty of liquefaction; barely five years after Dewar's initial success, he stated: "At the present time the transfer of hydrogen and oxygen into their liquid states poses no special problem."[9] He does not refer to Dewar's work, but he was aware of the liquefaction of air and the effect of low temperature on

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*His value for water converts into a heat of combustion of $144 \cdot 10^6$ J/kg for hydrogen, almost the same as obtained by Dulong in 1838.

†Using $\frac{1}{2}V^2=gh$, where V is velocity, g acceleration of gravity (9.81 m·s^{-2}), and h height in m. Solving for velocity gives Tsiolkovskiy's result. He did not allow for the thermal cycle efficiency of a rocket engine, which is on the order of 40 to 50 percent, although he did in a later (1911) paper.

‡He computed utilization as the kinetic energy of the empty rocket at burnout velocity divided by the kinetic energy of the propellant mass at its jet velocity. The mass ratio of 5 is a good value for modern rockets; the German V-2, however, had a mass ratio of about 3.

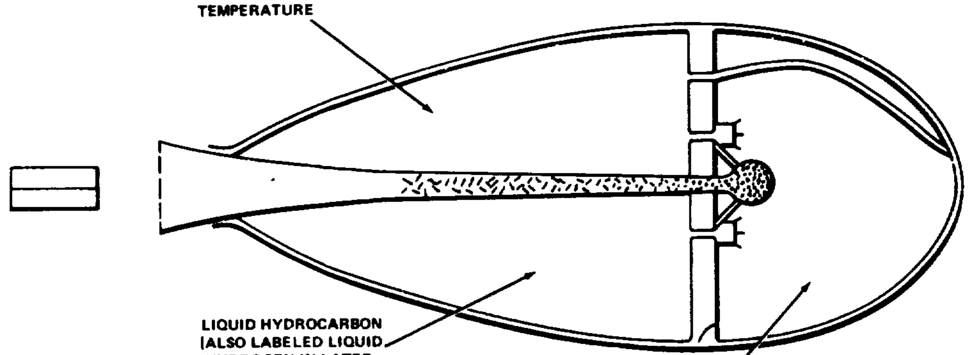

Fig. 60. Tsiolkovskiy's manned rocket, 1903. The rocket thrust chamber and a partition separate the fuel and oxidizer. The rectangles in the rear are rudders, part of the control equipment.

metals. He may have heard or read about Dewar's success in liquefying hydrogen—which would have been a feat for a secondary schoolteacher in a small Russian village.

Although liking hydrogen-oxygen, Tsiolkovskiy hedged his selection of it by observing: "The hydrogen may be replaced by a liquid or condensed hydrocarbon; for example, acetylene or petroleum."[10] The consideration of several candidate fuels characterized many of Tsiolkovskiy's later papers; as he became increasingly aware of the difficulties of using hydrogen, he gradually shifted away from it. In 1911, he observed that liquid oxygen could be obtained cheaply and so could gaseous hydrogen, but added: "The liquefaction of hydrogen is difficult (as of now), but it can be replaced with equal or even greater advantage by liquid or liquefied hydrocarbons such as ethylene, acetylene, etc."[11] Fifteen years later, he was even cooler towards the use of hydrogen:

> Liquefied pure hydrogen contains less potential energy, since it is cold and absorbs energy on turning into a gas, and its chemical effect is weaker. It is difficult to liquefy and store, since, unless special precautions are taken, it will rapidly evaporate. Liquid or easily liquefiable hydrocarbons are more favorable.[12]

In 1929–1930, Tsiolkovskiy published papers on rocket-propelled aircraft and argued that the way to the stars was to gradually increase the capability of aircraft from atmospheric to interplanetary flight. He discussed hydrogen, carbon, and benzene as fuels and felt it was a pity that liquid hydrogen was scarcely available.[13] In a still later paper, he considered hydrogen and light hydrocarbons as aircraft fuels, but expressed another problem when using hydrogen for aircraft:

> The fuels must be dense, so that they do not occupy much space. In this respect, liquid hydrogen is not suitable because it is 14 times lighter than water.[14]

A year before his death in 1935, Tsiolkovskiy submitted a paper in which he summarized his thinking about fuels for rockets.[15] He listed six properties a fuel should have: (1) maximum work per unit mass on combustion; (2) gaseous combustion products; (3) low combustion temperature to prevent chamber burnout; (4) high density; (5) liquid that readily mixes; and (6) if gaseous, must have high critical temperature and low critical pressure for use in liquefied form. He added that costly compounds should be avoided and found that hydrogen-oxygen satisfied all conditions except (4) and (6). Other fuels (methane, benzene, acetylene, and ethylene) were discussed, with a preference indicated for benzene and ethylene. Methanol, ethanol, ether, and turpentine also came under scrutiny; their high heats of combustion impressed him. Among oxidizers, he considered ozone, oxygen, nitrous oxide, nitrogen dioxide, and nitrogen tetroxide; of these, he liked nitrogen dioxide, an oxidizer much used in later rockets in the United States and elsewhere. Tsiolkovskiy also considered solid propellants, but rejected them on the basis of their low energy and danger of unexpected explosion. In his summary, he concluded: "Hydrogen is unsuitable because of its low density and storage difficulties when in the liquid form."[16] He might well have added his earlier comment about very limited availability. Many others who followed were to experience the same attraction for hydrogen-oxygen and abandon it for the same reasons.

While Tsiolkovskiy dreamed of spaceflight and published theoretical papers of very limited distribution, another man was dreaming of spaceflight, but with a difference. This man, also an educator, took rockets a giant step forward by adding practical experimentation to his ideas and theoretical calculations.

Robert Hutchings Goddard (1882–1945) suffered ill health during his youth in Massachusetts, but it did not deter his great love of experimental science.[17] His first experience with hydrogen came at sixteen when he was heating a tube containing hydrogen with an alcohol flame. Air must have entered the tube for it exploded violently, hurling glass fragments into the ceiling and through the door of his attic laboratory. His parents convinced him to redirect his interests, and he soon was experimenting with a pillow-shaped aluminum balloon filled with hydrogen; it was too heavy to rise.

At sixteen, Goddard began describing his experiments and calculations in a notebook—a lifetime practice that has provided a rich source of information. Like Tsiolkovskiy, Goddard had a dream about spaceflight that had a profound effect upon his life. His occurred in a cherry tree on his grandmother's farm on 19 October 1899, and from that moment spaceflight became his greatest single goal and the tree, the symbol of his resolve.[18]

In his student years (1904–1913) at Worcester Polytechnic Institute, Clark University, and a year of postdoctoral research at Princeton University, Goddard studied physics and chose thesis subjects that were more acceptable to academicians than rockets.[19] During this time, however, he continued studying rockets in his spare time. His initial experiments with powder rockets came during his undergraduate days. In 1907, he calculated the lifting of scientific equipment to a great height by a combination of balloon and rocket. Like Tsiolkovskiy, he was attracted to the hydrogen-oxygen combination because of its high energy. In 1909, he calculated that the energy from 45 kilograms of hydrogen-oxygen was sufficient to send a kilogram

payload to infinity. He also found that it took nearly 50 times as much gunpowder as hydrogen-oxygen for the same mission. Convinced of the potential of hydrogen-oxygen, he wrote in 1910 about a method for producing hydrogen and oxygen on the moon. Later he took out a patent for producing hydrogen and oxygen where there was ice and snow at low temperatures, such as high on a mountain. He proposed to generate the gases by electrolysis of water using solar energy.[20]

Goddard began his rocket experiments with gunpowder, by far the most convenient and available explosive, but he was soon attracted to the more powerful guncotton. In 1913, he compared it with hydrogen-oxygen:

> . . . it should be a comparatively simple matter to construct an apparatus using guncotton, having a net efficiency of 70 percent; which would require 500 lb initially to send 1 lb off the earth. . . . Hydrogen and oxygen, of course, give the greatest energy on burning, but the hydrogen would have to be liquid and the oxygen solid for the sake of lightness, and this would introduce difficulties which would more than offset the trouble of using a larger mass, with guncotton.[21]

By that time, he saw a much smaller performance gap between a practical solid propellant and hydrogen-oxygen and recognized the problems of obtaining and working with liquefied gases.

From 1915 to 1916, Goddard conducted a series of remarkable experiments, demonstrating for the first time that rocket efficiency increases in a vacuum. Elated with this success but sorely in need of funds, Goddard described his results and ideas for reaching extreme altitudes in an impressive report and sent it to the Smithsonian Institution with a request for financial support. He got the support and three years later his report, with added notes, was published by the Smithsonian. Unfortunately, he had much less success with his next series of experiments. It took four years of hard effort and many failures before he realized that he was on the wrong track. In all this time he had been firing solid propellant in a series of discrete explosions. He sought a mechanical method that would detonate the succession of charges in much the same way as a machine gun.[22] Such designs are not only mechanically difficult but also heavy.

In a report to the Smithsonian in 1920, Goddard pointed out that liquid hydrogen and solid oxygen had greater capability than smokeless powder for lunar and planetary missions.[23] He suggested that the liquid hydrogen–solid oxygen mixture might be enclosed in a capsule of solid smokeless powder. As previously mentioned, however, Goddard had difficulty with smokeless powder charges and the liquid hydrogen–solid oxygen mixture was not tried.

Goddard's failure to make a practical rocket using discrete charges of smokeless powder was a blessing in disguise, for it turned him to liquid propellants and continuous burning—the approach that led to his greatest successes. He abandoned discrete charges, and in July 1921 began experiments with continuous burning, working first with the familiar smokeless powder. By September, he had switched to liquids. He first considered alcohol as a fuel but never used it. Instead he chose ether because it had a lower boiling point and heat of vaporization—advantages for mixing

and combustion—and a higher heating value. He soon switched from ether to gasoline, and thereafter he stuck with the gasoline–liquid oxygen combination in building his flight rockets. On 1 November 1923, he static-fired a rocket using this combination pumped to the combustion chamber.[24]

In spite of Goddard's early interest in hydrogen-oxygen he did not operate a rocket with either gaseous or liquid hydrogen as the fuel. This was probably due more to his practical nature than to lack of interest. He had enough problems getting liquid oxygen for his initial experiments; liquid hydrogen would have been much harder to obtain, as well as expensive and difficult to handle.[25] He apparently was satisfied with his propellant combination and absorbed in the myriad other problems of building and flying a complete rocket vehicle—a highly complex task.

On 3 May 1922, nine months after Goddard began experiments with ether and oxygen in continuous combustion, he received a letter from another man obsessed with spaceflight, a man whose publication and priority claims a year later were to upset Goddard.

Hermann Oberth (1894–) became interested in space travel at the age of eleven when his mother gave him a copy of Jules Verne's *From the Earth to the Moon*. In the next two years he analyzed and discarded several methods for achieving spaceflight, including Verne's cannon, the pull of a powerful magnet on skids in a long tunnel lined with ice, and a wheel utilizing centrifugal force. He came to the conclusion that reaction propulsion was the only feasible method, but was dismayed by the problems of fuel consumption, handling of liquid fuels, hazards of solids, and the high cost of chemicals. These problems discouraged him from attempting experiments in his youth. Instead he turned to the theoretical analyses that are his lasting contributions to rocketry.

Oberth's educational experiences in Germany were unhappy. In his secondary schooling the emphasis was on the classics, with exercises requiring good memory and flawless writing, and he found it difficult to conform. He wrote a thesis on rocket propulsion for his doctor's degree at Heidelburg University, but it was rejected.

Oberth's career is marked with difficulties and lack of recognition for his contributions. In 1917, he submitted a proposal to the German War Department to build a long-range liquid propellant missile, but it was rejected as impractical. After his thesis was rejected, Oberth paid to have it published in 1923 as a pamphlet of less than one hundred pages with the title *Die Rakete zu den Planetenraumen* (The Rocket into Interplanetary Space). This was the publication that disturbed Goddard; but according to Oberth, it was largely ignored in Europe in the 1920s. Oberth became a secondary schoolteacher in 1923, but left a year later to accept a banker's offer to finance the building of his space rocket. After six months of indecision, the banker backed out, leaving Oberth disillusioned and broke. In 1929, a third edition of his book was published under the new title *Wege zur Raumschiffahrt* (Ways to Spaceflight). In 1929–1930, he served as a scientific advisor for the film *Frau im Mond* (Girl in the Moon) produced by Fritz Lang—a film that greatly influenced Krafft Ehricke when he was eleven (p. 191). The making of the film brought the opportunity to obtain funding for rocket experimentation. Oberth undertook to build a liquid-fueled rocket to be launched on the day of the film's premiere to publicize it, but time was too short and the

task too difficult. The film was a great success, but Oberth returned to relative obscurity.

In 1938, Oberth began working on military rocket development for the Germans. He went to Peenemünde about the time the A-4 (V-2) development was completed, but worked on solid rather than liquid rockets until the end of the war. The Allies, gathering up rocket experts, ignored Oberth, who returned to his family in Feucht. He came to the United States in 1955, where he worked quietly in Huntsville on rocket research, but returned to Feucht four years later.[26]

Oberth's 1923 book was based on his conviction that existing technology made possible rocket flight beyond the earth's atmosphere and that, with refinements, vehicles could carry man beyond the earth's gravitational field. He developed and improved the theory of rocket flight and performance. He proposed a space rocket having an alcohol-water mixture and liquid oxygen as the first stage propellants and hydrogen-oxygen as the upper stage propellants. With a remarkable insight into physical phenomena, his theoretical analyses were a great contribution to the general advancement of rocket technology. A number of his proposals were later adopted and put into practice. The slow acceptance of his theoretical work, the criticisms, and the controversies may have been due to his lack of academic credentials and the boldness of his proposals. His lost opportunities and experimental failures were probably due to his naïveté in politics and business as well as his lack of practical engineering experience. He deserves much credit for providing the theoretical basis for European rocket development and, later, space boosters. His first public recognition came from France, when the Société astronomique de France gave him the REP-Hirsch award in 1929, for the third edition of his book.*

Oberth recognized and showed the advantages of using multistage (step) rockets, an old concept, to achieve the very high velocities necessary for spaceflight. A step rocket is one rocket riding piggyback on top of another so that their velocity increases during burning are additive, a concept recognized as early as the seventeenth century.[27] The Tsiolkovskiy equation (p. 253) can be used to approximate the final velocity of a multistage rocket by considering each stage in succession. In addition to designing step rockets, Oberth also recognized that a rocket had greater thrust when operating outside the earth's atmosphere than within it and cited Goddard's experiments as proof.

One of Oberth's contributions is very helpful to a better understanding of rocket performance and the reason hydrogen makes such a good fuel. He applied the theory of gas flow through nozzles to rockets and cited Zeuner's *Turbinen* (Turbines) as his source.[28] Oberth was the first to publish the relationship for the case of a rocket, showing that the rocket exhaust velocity is a function of four variables: the pressure and the specific volume of the gases in the combustion chamber, the ratio of the specific heats (constant pressure to constant volume) of the gases (assumed to remain constant

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*The award, with a 5000-franc prize, was established that year by the famed French aviator and space pioneer Robert Esnault-Pelterie and banker André Hirsch for the experimenter who had done the most for spaceflight. Oberth was the first to win it. As a special compliment to him the prize was doubled. Ley, *Rockets, Missiles & Space Travel* (New York: Viking, 1961), pp. 23–24.

during the gas expansion), and the pressure of the expanded gases at the nozzle exit.* Using the perfect gas equation, rocket exhaust velocity can also be expressed as a function of three ratios: specific heat, nozzle exit pressure to combustion pressure, and combustion gas temperature to the mean molecular mass of the gases. Of these, the pressure ratio is determined by the rocket design; the other two depend upon the particular fuel and oxidant plus their relative proportions. Since the specific heat ratio varies over a relatively small range, the rocket engineer focuses his attention on the ratio of combustion temperature to mean molecular mass in comparing the performance potential of various propellant combinations. The exhaust velocity is proportional to the square root of this ratio—so the higher, the better. The rocket engineer also is concerned with cooling the engine and would like to keep the combustion temperature as low as possible without great sacrifice in exhaust velocity. He would, therefore, want to keep the mean molecular masses of the combustion gases as low as possible. This is where hydrogen excels, for it is the lightest of the elements. Exhaust gases rich in hydrogen exceed the performance of heavier gases at the same temperature.

Oberth liked the hydrogen-oxygen combination because it had the highest jet velocity of any combination he could find. The second best combination, he believed, was ethyl alcohol and oxygen. His choice of hydrogen-oxygen for the second stage of his space rocket and alcohol-oxygen for the first stage did not change as he refined and expanded his calculations from the first through the third editions, over a period of six years. The reasons for his choices, other than energy content, and his explanations—scattered in his book—are somewhat obscure and confusing. They involved considerations of propellant density, aerodynamic forces, choice of propellant mixture ratio, and the effect of these on mass ratio and performance. Oberth was well aware of the low density of hydrogen, its effect on structural volume and weight, and the effect of these, in turn, on aerodynamic drag and bending forces in flight through the atmosphere. For this reason, dense propellants were favored for the first stage, which, of course, had to start from the ground and fly through the atmosphere.

Oberth was also concerned about dissociation losses in the hydrogen-oxygen reaction. Dissociation is the breakup of molecules (in this case, water) into its elements, which occurs at high pressures and temperatures. It is an endothermic process—one that absorbs heat—so part of the heat released in the combustion process is absorbed by dissociation and therefore is unavailable for conversion into work. From structural and aerodynamic considerations, Oberth wanted to use the stoichiometric (exact proportion) mass mixture ratio of 1 part hydrogen to 8 of oxygen to have a high propellant density of the hydrogen-oxygen combination (of 1.02 kilograms/liter). The dissociation consideration, however, convinced Oberth that a hydrogen-rich mixture, 1 part hydrogen to 2 of oxygen, would be necessary for a first stage. Since this low

*Oberth's equation for exhaust velocity was

$$\sqrt{C\left(\frac{\gamma}{\gamma-1}\right) P_o V_o \left[1-\frac{P_e}{P_c}\right]^{\frac{\gamma-1}{\gamma}}}$$

where C is a constant, γ the ratio of specific heats, P_o the combustion pressure, V_o the specific volume, P_c the combustion pressure, and P_e the exit pressure. This equation can be obtained by algebraic combinations of the basic thermodynamic relationships of the equation of state for a perfect gas, conservation of energy, reversible adiabatic (isentropic) gas expansion, and specific-heat relationships.

propellant density meant structural and aerodynamic disadvantages, Oberth rejected hydrogen-oxygen for his first stage.

The situation with respect to dissociation for the upper stage rocket was different. A lower pressure could be used, which reduced the problem of dissociation. Oberth first believed he could use the stoichiometric mixture ratio to keep overall density at a minimum, but later, cooling problems led him to choose a hydrogen-rich mixture—1 part hydrogen to 1.43 of oxygen.[29]

He designed the second stage very light and fragile and protected it during the first part of the flight by enclosing it within the first stage. Oberth's analysis indicated that the alcohol-oxygen combination was superior to hydrogen-oxygen at lower altitudes, but at an altitude between 5500 and 8400 meters (1/2 to 1/3 atm), the hydrogen-oxygen combination became and remained superior.[30] He was right in choosing hydrogen-oxygen for upper stages, as later events showed.

In his writings, Oberth was fiercely defensive and made numerous references to apparent critics. He appeared particularly sensitive about the practicality of his designs. He sought to give just enough information to show that his rocket "could be built under all circumstances" and to show that he knew something about practical design, yet not give enough information so that someone else could build his rocket. He described his "Model B" rocket as more complicated than his "Model C," which he would not detail. Model B was a high-altitude meteorological rocket consisting of an alcohol-oxygen first stage and a hydrogen-oxygen upper stage. An "auxiliary" stage boosted it, so it really was a three-stage rocket. The hydrogen-oxygen stage was very small—a decided disadvantage in using low-density hydrogen. It weighed 6.9 kilograms and carried 3.3 kilograms of propellant—1.36 kilograms of which was liquid hydrogen. The hydrogen tank, made of a copper-lead material 0.0144 millimeter thick, had a capacity of about 19 liters; Oberth specified its weight as 33 grams. He provided a hydrogen pump to generate 5 atmospheres pressure and specified its weight, plus the oxygen tank and reinforcements, as 0.5 kilogram.[31] Oberth's sketches and description give few details. These specifications would severely tax the skills of an engineer even with today's advanced technology. In fairness to Oberth, however, his tanks were light because he conceived the idea of using internal pressure for reinforcement (like a metal balloon). A quarter of a century later, the same basic idea appeared in several U.S. designs and is used today in the Atlas and Centaur vehicles.

Although often citing experiments by others to support his statements, Oberth seldom mentioned his own experiments or revealed details about them. He apparently experimented with a gaseous hydrogen–oxygen burner. In responding to a critic who claimed that jet speeds beyond 2000 meters per second were impossible, Oberth stated he had achieved velocities of 3800–4000 meters per second with a gas burner. Later, in discussing a design for a mail rocket, he observed: "For example, with a correctly built oxygen-hydrogen nozzle I achieved a burn lasting 21 minutes." In describing another design in 1929, however, he stated: "Unfortunately, I have not yet been able to experiment with liquid hydrogen."[32]

Regardless of the practicality of his design or the lack of experimentation, Oberth's contributions represented the most comprehensive theoretical analyses of rockets available; Tsiolkovskiy's earlier publications were practically unknown outside Russia, and Goddard's principal rocket publication up to that time was the 1919

Smithsonian paper. Oberth's publications did much to stimulate others to work on rockets.

Like Tsiolkovskiy and Goddard, Oberth wrote imaginative versions of space travel to popularize the subject. In his 1929 book he spun a yarn about a rocket flight around the moon. The rocket, which used hydrogen-oxygen, was to ascend from the Indian Gulf. He relates an incident that could apply to present-day interest in hydrogen:

> When I arrived . . . I was suprised to see the many automobiles which caused neither fumes nor noise and, in spite of their sometimes considerable speed, seemed to have extremely small and light motors.
>
> Well remember . . . we have liquid hydrogen and oxygen factories. . . . All these automobiles have hydrogen motors. . . .
>
> Yes, but is not all the hydrogen produced by the plants needed for the rocket?
>
> At first . . . no large rockets were launched for months. To prevent our hydrogen plants from being completely idle in the meantime, we sought to utilize at least part of the liquid hydrogen in industry. . . . Today we can hardly fill the demand. We are obliged to enlarge the plants almost every month.[33]

After Oberth wrote to Goddard on 3 May 1922, Goddard replied and enclosed a copy of his 1919 Smithsonian paper. When Oberth's book appeared in 1923, he sent Goddard a copy. An addendum to the book deals with Oberth's becoming aware of Goddard's work and stating the independence of his work. His book disturbed Goddard, who never overcame his adverse reaction to Oberth.[34] It stimulated Goddard to prepare an addendum to his 1922 Annual Report to Clark University, and he sent a copy of it to the Smithsonian. It was a response to Oberth's work and contained details of experimental work not mentioned in his own previous reports. He described his first liquid-propellant experiments with ether as the fuel. Although he mentions Oberth's proposal to use hydrogen-oxygen and his own considerations of this combination, he did not mention any work, past or contemplated, using either gaseous or liquid hydrogen.[35]

In 1929, Goddard submitted supplementary notes to his 1920 Smithsonian report indicating that he experimented with continuous burning of liquid propellants in 1920. He added that "continuous combustion by the use of hydrogen and oxygen was first considered by the writer several years ago, in June 1907, and was patented in 1914." As in 1920 and 1922, however, he made no mention of experimental work with hydrogen-oxygen.

To sum up, Tsiolkovskiy, Goddard, and Oberth—the pioneers in the history of rocket technology—represent both the theoretical and the practical side of rocketry. They not only had their consuming interest in rockets in common, but Tsiolkovskiy and Goddard had inspirational dreams about space travel, and all three wrote popularized accounts of space travel. All three were educators; two were secondary schoolteachers, one a college professor. All three were attracted to hydrogen because of its high energy, but theoretician and experimenter alike saw its disadvantages of low availability, low density, and difficulty in handling. Goddard, the only one of the three

to experiment extensively with liquid propellants in continuous combustion, passed over hydrogen in favor of gasoline—most likely because of gasoline's availability and ease in handling. Hydrogen, then, successively attracted and disillusioned rocket investigators. This pattern of attraction-repulsion is repeated many times in the history of hydrogen as a flight propulsion fuel.

Although Tsiolkovskiy, Goddard, and Oberth were perceptive in seeking hydrogen's advantages as a rocket fuel, advancements in hydrogen technology useful for flight applications came from other concurrent activities, one of which was development of the dirigible.